

The search for extra-terrestrial sources of high energy neutrinos

Gary C Hill

University of Wisconsin, Madison

The field of high-energy neutrino astronomy has seen rapid progress over the last 15 years, with the development and operation of the first large-volume detectors. Here, we review the motivation for construction of these large instruments and discuss what construction and physics progress has been made.

I. WHY NEUTRINO ASTRONOMY?

We live in a mysterious universe – one that abounds with many objects that seem to involve extremely high-energy processes – accretion of matter into black holes at the centres of active galaxies, supernovae and gamma-ray bursts, where enormous amounts of energy are released over time scales as short as a few seconds. Understanding these objects and the processes therein involves observing high-energy radiation and particles. Our three particle messengers we have for high-energy astronomy are charged cosmic rays (protons and nuclei), gamma-rays and neutrinos. While we have large amounts of data from cosmic ray and gamma-ray observations, the nature of their sources is still not completely understood. It is the neutrino that may provide the connection.

The cosmic rays – high energy protons and nuclei – have been well studied at earth with both space and ground-based detectors. Their major astronomical disadvantage is that they are charged, and thus except for the very highest energy protons, they spiral around in magnetic fields during their passage to earth, which means that knowledge of their original direction is lost. High-energy gamma-rays have been detected from many galactic and extra-galactic objects but their usefulness as a messenger over long cosmic scales is limited by their absorption on the extra-galactic background light.

The Auger cosmic ray detector[1] in Argentina is the culmination of nearly a century of effort studying the high energy cosmic ray particles. The array combines for the first time the two key techniques used over recent decades - a ground based air shower particle detector and a series of air fluorescence detectors, which observe light emitted as the air showers develop in the atmosphere. The combination of the two techniques has provided an essential energy calibration for the ground array. The Auger experiment has published a correlation analysis which hints that the highest energy cosmic rays might be associated with nearby active galaxies[2].

The high energy gamma-rays are detected using large area ground based telescopes, which either image the Cerenkov light released from air showers created by the interaction of the gamma-rays in the atmosphere, or measure the arrival of the shower particles at the ground. The Milagro detector[3] uses

a large pool of water to measure the shower particles at the ground. It has a large sky coverage and has successfully detected sources of high energy gamma rays, including several in the galactic plane and one very bright source in the Cygnus region[4]. The HESS[5], MAGIC[6] and VERITAS[7] telescopes image the shower Cerenkov light pool directly and have observed many sources, both galactic and extra-galactic[8].

If one of these gamma-ray sources was found to be a neutrino source, then a hadronic accelerator central engine might be simultaneously driving cosmic ray, gamma and neutrino production from the one object[9].

The road to a kilometre-scale neutrino detector, pioneered by the DUMAND collaboration, has seen the operation of the first generation experiments, AMANDA and Lake Baikal, as well as initial construction and planning for IceCube, ANTARES, NESTOR, NEMO and KM3NET. The discovery of neutrinos with these detectors will hopefully extend and complement the knowledge of the universe to date gained through cosmic ray and gamma ray observations.

A large volume neutrino detector uses an array of photomultipliers to record Cherenkov light from through-going muons, or from point-like shower (“cascade”) events. Muons result from charged current interactions of neutrinos in the detector volume, or in the surrounding ice and rock. Cascade events result from charged and neutral current interactions of all neutrino flavours.

The backgrounds to a search for a flux of high-energy extra-terrestrial neutrinos at the earth are atmospheric muons and neutrinos from the interaction of cosmic rays in the earth’s atmosphere. The atmospheric muons are eliminated by looking for events moving upward through the detector – only neutrinos can penetrate the earth. A small fraction of the large downgoing muon flux will be falsely reconstructed in the upward direction. These are removed by tight requirements on the fitted track - where only the most neutrino like events are kept. After atmospheric muons are eliminated, there is a flux of atmospheric neutrinos seen in a detector. This can be used as a calibration test beam to check the understanding of the detector, or be used to look for new neutrino physics. A search for point sources of neutrinos is made by looking for an excess of events from a

direction in the sky. Electromagnetic observations by other detectors may provide information to reduce the time over which such a search is made - for instance in a search for neutrinos correlated with gamma-ray bursts. One can also look for a diffuse excess of neutrinos from the sum of all sources in the universe. Since the extra-terrestrial flux predictions tend to go as $dN/dE \sim E^{-2}$, one looks for higher energy events in the detector to separate them from the more steep atmospheric neutrino spectrum ($dN/dE \sim E^{-3.7}$).

II. NORTHERN-HEMISPHERE DETECTORS

The Baikal collaboration has constructed a neutrino detector in the deep fresh water lake Baikal in Siberia[10]. In the winter, the surface of the lake freezes over allowing the team to move equipment out to the site and lower the strings of detectors to the bottom of the lake. The detector has operated for many years and has produced limits of the fluxes of diffuse neutrino sources. In the energy range ($20 - 5 \times 10^4$ TeV), the Baikal collaboration has analysed 1038 days (1998-2003) of data from the NT-200 experiment, leading to a limit on a diffuse flux of neutrinos from the sum of all sources in the universe of $E_\nu^2 \times dN_\nu/dE_\nu = 8.1 \times 10^{-7}$ GeV cm⁻² s⁻¹ sr⁻¹[10].

The ANTARES detector[11], located in the deep Mediterranean ocean, has been recently completed[12]. This consists of 12 lines, a total of 900 optical modules. The optical modules are deployed in triplets (a “storey”) spaced at 14.5 metres. Deployment of each line is done from a ship, which lowers the line to the ocean bottom. After that is completed, a miniature submarine is used to complete the electrical connection of the line into a junction box, from where data is transmitted back to a shore station via an undersea cable. The array of optical modules slowly sways back and forth in the ocean currents, leading to the necessity of a short-scale active calibration system to record the geometry for later use in event reconstruction. Sources of noise include bioluminescence, which is reduced by requiring coincidences of optical modules in a triplet line unit. The array was completed in May 2008, with the installation of the final two lines. Data from 10 lines, taken over 100 active days of operation from December 2007 to April 2008, showed that upgoing atmospheric neutrinos could be isolated in the data set. First physics analyses are underway. The sky coverage of ANTARES is complementary to the south polar detectors, leading to a combined full sky coverage. Importantly, ANTARES has a full view of the galactic centre, where many interesting gamma-ray sources have been observed with HESS.

There are two other ongoing projects in the Mediterranean - NEMO[13] and NESTOR[14]. Both are still in the prototyping and construction phase. Together,

the three Mediterranean groups have begun development of a proposal for KM3NET – a kilometre scale Mediterranean detector[15].

III. ANTARCTIC DETECTORS

A. Optical Cerenkov detectors: AMANDA and IceCube

The first detection of muon Cherenkov radiation in polar ice was made in Greenland in 1990 [16], using three photomultipliers deployed to a depth of about 200 metres. Following this success, similar tests were made at the South Pole over the next years, with the AMANDA-A detector deployed in 1993-94 [17]. Construction of the presently operating AMANDA-II detector took place from 1995 to 2000, over which time 677 optical modules were deployed over 19 strings, to depths ranging from 1500 to 2000 metres. The properties of the polar ice, critical for understanding of the detector, have been measured using light sources in the array [18]. Although most of AMANDA used analogue signal technology, digital technology, eventually chosen for IceCube, was tested on one string [19].

While three neutrino candidates were observed with the first four strings of AMANDA [20], the first compelling evidence of high-energy atmospheric neutrinos came from the 10 string 1997 data set, where 16 upgoing events were left after data reduction [21]. Dramatic improvements in the analysis techniques [22] increased this number to about 300 [23, 24]. Over the entire life of AMANDA-II, many thousands of atmospheric neutrinos have now been observed [25, 26]. These are the highest energy neutrinos ever observed. The observed rate is consistent with the uncertainties in theoretical predictions [27, 28]. A regularised unfolding technique has been used to make a best-fit to the originating energy spectrum; again consistency with expectation is seen [29]. The agreement of the atmospheric neutrino measurements with expectations shows that the detector is working as expected.

Several searches for northern hemisphere point sources of neutrinos have been conducted with the AMANDA detector, for the 1997 [30], 2000 [31], 2000-02 [32] and 2000-04 data sets[25, 26]. Several search methods were used to look for point sources in the northern sky. For each, the expected background for any source is found from off-source data from the same declination band. The expected sensitivity is found from simulations of neutrino interactions, muon propagation, and the full detector response to the Cherenkov light emitted. Full-sky searches (looking for a hot spot anywhere in the sky), specific source searches, and stacking searches were conducted. The full-sky and specific source searches were optimised in an unbiased fashion to produce the best limit setting

potential [33]. The 90% confidence level sensitivity of the full-sky search to an E^{-2} flux (assumed to have a $\nu_\mu : \nu_\tau$ ratio of 1:1), relatively constant with declination, is about $E_\nu^2 \times dN_\nu/dE_\nu < 10^{-10} \text{ TeV cm}^{-2} \text{ s}^{-1}$. The numbers of observed events across the sky were consistent with the background expectations, leading to the same result for the average all-sky experimental limit. The highest significance seen was 3.7σ and, via scrambled random sky maps, the probability of seeing something this significant or higher was found to be 69%. Searches for 32 specific candidate sources, and searches made where the events from objects belonging to common classes were summed, were made. Limits were placed on the neutrino fluxes from the objects [26, 34]. For a source above the horizon, SGR 1806-20, a search for muons from both neutrinos and gamma-rays was made. With no significant signal seen, limits were placed on the gamma and neutrino fluxes from the source [35]. While not truly a point source, the galactic plane was searched for an excess of neutrinos from cosmic ray interactions with the dust, using similar methods as employed in the point source searches. No excess of events was seen and limits on models were set [36].

Most recently, a new point source analysis was performed on the full AMANDA-II data set, for the years 2000-06[37]. This work used a full maximum likelihood fit, using the measured angular error of the reconstructed events and an energy dependent variable in the likelihood construction to increase the sensitivity to sources. No evidence for any sources was seen but the improved methods resulted in better limits than previous angular-binned analyses.

Gamma-ray bursts are some of the most energetic phenomena in the universe, with emission timescales as short as seconds. During the life of AMANDA, satellites such as the CGRO, with the BATSE detector, and the IPN satellites, including HETE and Swift, have recorded gamma emissions from many GRBs. Waxman and Bahcall theorised that GRBs may be the source of the highest energy cosmic rays [38]. In this “fireball” model, neutrinos would also be produced. The AMANDA data has been searched for neutrinos in spatial and temporal coincidence with about 400 GRBs [39]. The addition of a time cut on the search greatly reduces the expected background to an order of one event over the sum of all GRBs searched. No event has been observed in coincidence with a GRB, consistent with this small total expected background. Limits on the fluxes from all bursts, classes of bursts, and individual bursts, have been placed. The limits from all bursts are within a factor 4 of the Waxman-Bahcall prediction. In another analysis, the observations from each individual burst are interpreted in light of all information known about that burst from other wavelengths, via an individually calculated neutrino flux. An analysis of this type has been performed for GRB030329 [40]. The study of further GRBs is in

progress. Searches for cascade like events from GRBs have been made [41]. All-time and rolling time window searches have been performed and limits placed on models of neutrino production.

The mystery of the dark matter, responsible for some 23% of the energy density of the universe, is a target of the search for WIMPs (Weakly Interacting Massive Particles) with AMANDA. A likely dark matter candidate is the neutralino - the lightest supersymmetric particle in most supersymmetric extensions of the standard model. After some time, these would become gravitationally trapped in the centre of the earth and sun, where they could pair-wise annihilate via several paths to produce neutrinos. Thus, AMANDA is used in searches for excesses of neutrinos from the centre of the earth (1997-99 data [42, 43]), and from the sun (2001 data [44]). To date, neither the earth nor sun has been revealed as an annihilation site for neutralinos, and these non-observations place bounds on various parameters in the supersymmetric extensions of the standard model. Once all current data is analysed, these bounds will be competitive and complementary with those from direct detection experiments like CDMS.

To search for a diffuse flux of neutrinos from the sum of sources in the universe, one must look for neutrinos in excess of the expectation for atmospheric neutrinos. The extra-terrestrial flux is expected to have a harder spectrum ($\sim E^{-2}$) than the atmospheric neutrinos ($\sim E^{-3.7}$), so searches are designed where event energies are estimated. Three types of diffuse search are conducted with AMANDA, one sensitive to muon-neutrinos, and the other two sensitive to all flavours. The muon search seeks to isolate muon tracks and use event observables related to the energy. One style of all-flavour search focuses on cascade-like events - and is thus sensitive to neutral and charged current interactions of all flavours. Cascades from charged current interactions come from electron and tau neutrinos, and from some muon-neutrinos where most of the energy goes into the cascade, leaving only a short track from a low energy muon. These searches are mostly sensitive to cascade events contained in the detector volume. The second type of all-flavour search looks for large cascade and muon events from extremely high energy neutrino interactions, including events where the cascade or muon is well outside the volume of the detector. Due to attenuation of neutrinos in the earth, these searches are most sensitive to horizontal events, with the main background being energetic cosmic ray muon bundles.

Unlike a point source search, a diffuse search strictly has no “off-source” region where data can be used to estimate the background. Thus the analysis relies on theoretical predictions of the atmospheric neutrino fluxes for background estimations. In practice, the observed lower energy events are used to place some constraint on the atmospheric models before they are

used to estimate the high energy background. As for other analyses, downgoing muons are used as a calibration beam to check that the detector would be sensitive to the types of high-energy events expected from extra-terrestrial neutrinos.

Two *all-flavour cascade* searches have been performed, on the 1997 [45] and 2000 [46] data sets. The limit for the 2000 data improved by an order of magnitude over that for 1997. In a similar energy range ($20 - 5 \times 10^4$ TeV), the Baikal collaboration has recently analysed 1038 days (1998-2003) of data from the NT-200 experiment, leading to a slightly better limit of $E_\nu^2 \times dN_\nu/dE_\nu = 8.1 \times 10^{-7}$ GeV cm⁻² s⁻¹ sr⁻¹ [10].

At higher energies, these data sets have been analysed with the *all-flavour UHE* method [47, 48, 49]. Although the sensitivity of the 2000 search ($E_\nu^2 \times dN_\nu/dE_\nu = 3.7 \times 10^{-7}$ GeV cm⁻² s⁻¹ sr⁻¹) was improved over 1997, the experimentally obtained limit for 2000 turned out to be the same as that for 1997, due to the observation of a non-significant excess of events. These limits are the best of any detector at energies up to ~ 1 PeV.

Searches for a diffuse flux, using reconstructed contained muon events, have been made on the 1997 [50], 2000 and 2000-03 data sets. For the year 2000 data set, a regularised unfolding of the energy spectrum was conducted. This spectrum was statistically compared with the atmospheric neutrino expectation and a limit on a diffuse E^{-2} flux derived [29]. For the 2000-03 data [51], the muon analysis used the number of optical module channels per event that reported at least one Cherenkov photon (N_{ch}) as an energy estimator. The harder expected extra-terrestrial flux would produce a flatter N_{ch} distribution than that for atmospheric neutrinos. Before looking at the data, an optimal cut of N_{ch} was found in order to produce the best limit setting sensitivity of the search [33, 52]. The data above this cut ($N_{\text{ch}} > 100$) were kept blind while the lower N_{ch} events were compared to atmospheric neutrino expectations. The Bartol [27] and Honda [28] atmospheric neutrino fluxes were varied to account for systematic uncertainties, then constrained by normalisation with the low N_{ch} data. The remaining spread in the high N_{ch} region was used to calculate an error on the expected number of events above the $N_{\text{ch}} > 100$ cut. Above the cut, 6 events were seen, where 6.1 were expected. Using the range of atmospheric uncertainty in the limit calculation [53] leads to a limit on an E^{-2} flux of muon-neutrinos, at the earth, of $E_\nu^2 \times dN_\nu/dE_\nu = 8.8 \times 10^{-8}$ GeV cm⁻² s⁻¹ sr⁻¹. This limit is valid in the energy range 16-2500 TeV and is the best limit of any neutrino detector to date. Limits were also placed on specific extra-terrestrial models and on the flux of prompt, charm-meson neutrinos from the earth's atmosphere [54].

AMANDA is a supernova detector, with sensitive coverage of our galaxy [55]. A burst of low energy

electron-neutrinos from a supernova would produce an increase in the rates of all optical modules over a short time (~ 10 seconds). The AMANDA supernova system is part of the Supernova Early Warning System (SNEWS). AMANDA, in conjunction with the SPASE surface air shower detector, has been used to study the composition of cosmic rays near the knee [56]. Searches for magnetic monopoles have been made, and Lorentz invariance and decoherence are two of the “new physics” tests being conducted with atmospheric neutrino data from AMANDA.

The first of the next generation kilometre scale neutrino telescopes, IceCube [57], will consist of an in-ice cubic kilometre neutrino detector, and a kilometre square surface cosmic ray air shower detector (IceTop). Construction began at the South Pole during the austral summer 2004-05, with 1 in-ice string, and 4 IceTop stations deployed [58]. The goal is to complete construction in early 2011, with 80 strings (4800 modules) and stations (320 modules) completed. The in-ice strings will instrument a kilometre volume between 1500 and 2500 metres depth, and the IceTop array will cover a square kilometre at the surface. The same design of DOM (Digital Optical Module) is used throughout the detector. These consist of pressure spheres containing 10 inch photomultiplier tubes, the signals of which are digitised inside the module and then sent to the surface data acquisition system. The DOMs differ from the AMANDA modules in that the full time series of photons (the “waveform”) is captured.

The holes are drilled with a hot water system, taking about 30 hours to drill to the final depth, then 10 hours to ream back up, depositing more energy to leave a hole at the correct size during the string deployment. Deployment of a string now takes about 4-9 hours - 3-7 hours for module attachment, then 1-2 hours to lower to the final depth. IceTop tanks are installed in shallow trenches dug near each string location, and are filled with water, which is allowed to slowly freeze back about the modules, to prevent formation of bubbles.

The deployed hardware has performed up to expectations to date. Detailed studies of the first string and IceTop tank behaviour have been published [58]. Even with one string, upward moving events were detected, consistent with an atmospheric neutrino origin. After this initial season, subsequent seasons have seen 8, 13 and 18 strings deployed for a current total of 40 strings. Air showers have been reconstructed with IceTop, and coincident events, where IceTop sees an air shower and the in-ice array sees the penetrating muons, have been studied. The 40 string array has been running for more than six months and data analysis has started. Analyses of the 9 and 22 string data have been completed, with no evidence of any sources seen.

An initial potential performance study for the in-

ice array of IceCube was completed before construction began [59]. The simulation and reconstruction programs were those used in AMANDA, adapted to the larger IceCube detector. As such, no usage of the DOM waveform information was made in the reconstruction. The assumed flux of charm atmospheric neutrinos [60] was chosen conservatively; if in reality this background turns out smaller, then the predicted sensitivities will be better than those quoted. A median angular resolution of better than 1° is seen for muon energies greater than 1 TeV. The effective area for muon detection exceeds the geometric kilometre area at 10 TeV, rising to 1.4 square kilometres for events in the 1 to 100 PeV energy range. The sensitivity to diffuse and point sources of neutrinos has been estimated. For three to five years of observation, the limit on an E^{-2} flux of diffuse neutrinos would be about thirty times smaller than the AMANDA-II four-year muon limit, and a flux one-tenth of the AMANDA-II limit would be detectable at 5σ significance in that time. For point sources, similar results are obtained. For GRBs, the Waxman-Bahcall flux would be constrained after the observation of about 100 GRBs, and 500 GRBs would be needed to observe that flux at a 5σ significance.

B. Radio-Cerenkov detectors: RICE and ANITA

At extremely high energies, the interaction of an ultra-high energy neutrino with the antarctic ice can produce coherent Cerenkov light in the radio frequency range. The first detector to exploit this principle was RICE (Radio Ice Cerenkov Experiment) which was deployed at the south pole. RICE consists of radio receivers which are deployed to shallow depths in some of the AMANDA holes. No events consistent with a neutrino interaction have been seen and thus

limits have been placed on the expected numbers of such neutrinos.

The ANITA experiment[61] takes the radio concept into the skies above Antarctic. Radio receivers are flown on a balloon up to about 100000 feet, from which a large volume of ice is observable. Two flights have occurred so far: the test flight of the smaller-scale ANITA-lite[62] and then a full ANITA mission[63], launched December 15th, 2006 and flown for 35 days. The analysis of these data has been completed. Whilst there no physics backgrounds at the sensitive energy range of the experiment, there are many possible man-made backgrounds across the continent which must be eliminated. After analysis of the data, no candidate neutrino events were found. Limits were placed on the fluxes of neutrinos at the highest energies.

The radio technique is being further pursued in Antarctica: there will be another ANITA flight and studies are underway for further in-ice detectors. Development work is underway for large arrays of buried-surface or shallow-hole receivers on the Ross ice shelf, or spread over a large area centred on the IceCube detector.

IV. CONCLUSIONS

The long-held dream of a large volume, high energy neutrino detector is finally a reality at several sites around the world. The last decade has seen great progress in technology, deployment, and analysis technique development for these detectors. The Lake Baikal, ANTARES, AMANDA, RICE, IceCube and ANITA detectors are operational and producing physics data. These detectors have unprecedented sensitivity to sources of extra-terrestrial neutrinos, which will hopefully lead to new discoveries about the nature of the cosmos.

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